Nuclear Heating Plants – an Option for District Heating in Future?

By Alfred Voß and Tobias Kohler, Stuttgart*)

Introduction

For different reasons the substitution of fossil fuels in the energy system of the Federal Republik of Germany which has a large market share in the heat market is an objective. Besides of the heat extraction from nuclear power plants the development of combined heat and power generation plants in high-temperature reactors and the heat production in heating reactors offer new perspectives for the use of nuclear energy for heat production. This paper presents the stage of development, the potential for application and the economic background of nuclear heating plants. These heating reactors are mainly designed to feed into typical district heating networks of the public utilities which are operated at temperatures of up to 120 to 130 °C.

State of engineering of heating reactors

A number of heating reactors has been developed lately applying different technical concepts. The extensive developmental work on some concepts for nuclear heating plants has come to a point where the executive planing could start in case of an order [1]. The requirements by district heat systems that determine the conception of nuclear heating plants are quite different from those for large nuclear power plants for the production of electricity:

- *small local networks partly with several feeding points,*
- *going along with this small heat capacity for the feeding heat source,*
- *comparatively low temperature level and*
- *long periods of load change.*

Figure 1 *shows different concepts of nuclear heating plants including their power range. There are concepts for heating reactors ranging from 2 MW to 500 MW so that nuclear heat sources are provided for all low temperature heat applications. Besides of the pebble-bed reactor (GHR, HTR) which can also be used for district heat supply most of the concepts base on the light-water reactor principle.*

All heating reactors have the following features in common:

- *an intermediate circuit which connects the primary circuit and the district heating grid and which avoids the spreading of possibly escaping activity,*
- *conservative layout of the reactor parameters,*
- *low specific fuel stress because of small power units and low pressure and temperature,*
- *removal of decay heat by natural circulation,*
- *no necessity for emergency power unit to supply active components for emergency cooling and*
- *long operation cycles.*

Several concepts additionally have an underground design which mainly provides protection against external effects e.g. aircraft crash.

The NHR (Nuclear Heating Reactor) by Siemens with 200 MW will serve as an example for a light-water reactor [2]. Figure 2 *shows a section through the reactor building which indicates the plants dimension. The primary circuit is operated in natural circulation and it has an operating pressure of 1.5 MPa and a nominal temperature of 200 °C. The control rods and their drives are totally integrated in the reactor pressure vessel* (figure 3).

The centrepiece of the nuclear heating plant is the reactor pressure vessel including the installation of the primary circuit and the containment vessel which tightly encloses it. The core is located at the bottom of the reactor pressure vessel and it consists of shortened fuel and control elements of the BWR-type. Straight-tube heat exchangers of the cross-flow-type transmit the heat to the intermediate circuit. The

*) *Prof. Dr.* A. Voß *is Head of the Institute for Energy Economics and the Rational Use of Energy (IER) at the University of Stuttgart, Dipl.-Ing.* T. Kohler *is Scientist at the IER, University of Stuttgart.*

After a lecture given at the AGFW lecture conference on 7 June 1990 in Karlsruhe.

pipes leaving the vessel radially are the water inlet and outlet for the intermediate heat exchangers. The heat is not drawn out of the vessel by pipes carrying water of the primary circuit. Since a loss of coolant can't occur corresponding security devices are not necessary.

Because of the low pressure of the primary circuit and its integrated arrangement the containment vessel can enclose the pressure vessel very tightly. This is why the reactor core will stay covered with water after any postulated primary leak within the containment. This is very important for the security of the plant.

The natural circulation principle allows a low heat rate of the fuel and low fuel temperatures. Together with the application-related operation mode which only demands slow load changes this leads to the expectation of extraordinarily low primary coolant radioactivity content.

Three independant lines are available to remove the decay heat from the shutdown reactor. These decay heat removal lines are connected to the intermediate circuits and will be activated by motor-driven valves. The decay heat can be transferred via the intermediate circuit and aircoolers to the environment by means of natural circulation.

The NHR is designed to be refueled once after the fuel life time of 20 years and the fuel elements of the spent first core remain in the reactor pressure vessel.

Most concepts for heating reactors are designed on the base of low power density and there are large water reserves provided. These are the reasons why there is sufficient long time available for the control of events beyond design in a heating reactor – quite different from large nuclear power plants for electricity production. So nuclear heating plants have a high safety standard even though there are no costly systems for emergency cooling or decay heat removal.

Looking at the basic security conception of heating reactors it seems to the possible to design the plants in a way that excessive release of activity can quasi-deterministically be excluded and that effect of events beyond design stay limited to the plant itself. This security aspect which is very important for the acceptance should be proved by complete risk analysis and should be demonstrated in practice.

We can look back on practical experience of running heating reactors and comparable plants: A research reactor was used for the production of process heat in Karlsruhe. At the moment there is a demonstration plant of the slowpoke-type with 2 MW in trial operation in Canada. In 1989 a test plant with a power of 5 MW started its test and power operation in China. Two plants of each 2 × 500 MW applying the AST-500 reactor type are under construction in the USSR and at the moment examination by international committes regarding security is going on. From 1963 to 1974 a heat (80 MW thermic) and power (12 MW electric) producing reactors was in operation in Sweden. Another reactor produces up to 26 MW of process heat in Norway since 1959 [3].

Demands on nuclear heating pants and their integration

For practical application nuclear heating plants must satisfy further requirements besides security. These requirements consider environmental and ecomonic aspects as well as the sustainable use of resources and reliability.

The investment cost dominates the heat generation cost of nuclear heating plants. This is why heating reactors represent typical base load heat sources. To study the integration of a heating reactor into a typical district heat demand represented by an annual load duration curve a model analysis was carried out. Figure 4 *shows the maximal power of the heating reactor in relation to the annual peak load and the heat fed by the reactor in proportion to the annual heat demand both depending on the requested reactor peak load utilization time.*

A nuclear heating plant will be implemented in a rational way as a base load heat source when it reaches a peak load utilisation time of 4000 hours. The reactor then supplies a power of approximately 50% of the annual peak demand and feeds about 90% of the annual heat demand. The peak load and standby capacity and roughly 10% of the annual heat will be supplied by a fossil system.

Can heating reactors be implemented economically?

Nuclear heating plants are in competition with most low temperature heat sources. In the district heating system these are heating plants and combined heat and power plants. When competing with the domestic heat production all components of the district heating system must be taken into account which are both base load and peak load heat producer, heat transport and distribution and house service connection.

For the economic analysis the average finance mathematical heat production cost is calculated on the basis of the dynamic annuity method. Cost base is the year 1987 and all calculations consider the national economic point of view. It is assumed that all systems start operation in the year 2000. According to the real development of fossil fuel prices in the period from 1987 to 2010 an increase of almost 100% is assumed for oil products, 77% for German hard coal and about 12% for imported coal.

A proper economic analysis requires the consideration of the same system borders for all compared systems. For the base load and peak load and the domestic heating system different rates of utilisation are taken into account.

Unlike for fossil heat sources, the cost for nuclear heating systems is not covered by practical experience. The information on investment cost ranges between 2500 DM/kW for heating reactors with a power of 10 MW and 1000 to 800 DM/kW for plants with 100 to 400 MW. This cost seems to be achievable since heating reactors are technically much more simple than nuclear power plants which cost about 1100 DM/kW.

The heat production cost in combined heat and power generation plants often determines the level of district heating prices. The cost of the cogeneration products electricity and heat depends on a valuation which might reveal different heat prices depending on the defined price of electricity. Since the monetary value of electricity changes in reality from case to case the economicalness of nuclear heating plants can only be evaluated regarding the existing local circumstances.

The presented heat generation cost from combined heat and power production plants bases on an electricity credit according to the electricity production cost in a large nuclear or import coal fired power plant running a utilisation time of 4000 h/a.

In figure 5 the results of the economic comparison of heat production in several different sources is shown for plants going into operation in the year 2000. The specific investment cost degresses on rising plant power which results in a range of heat cost of the examined heat production systems shown in figure 5. The effect of an increase of investment cost by 50 % on the heat generation cost of nuclear heating plants is shown too.

The heat production cost of small reactors (10 MW) shown in figure 5 considers an unmanned or remote controlled operation mode. The heat generation cost would rise by about 60 % if licensing requirements would demand a fulltime crew.

The underlying economic assumptions prove that heating reactors are an economically competitive alternative to fossil systems in particular when looking at large reactors. Even tough the calculation of heat production cost in heating reactors bases on uncertain data the carried out economic comparison shows that from todays point of view nuclear heating plants have potential for an economic implementation in the district heating system.

Potential for the use of nuclear heating plants

Heating reactors are designed to feed into district heating networks so that the district heating industry occurs to be the main field of their application. Nuclear heating plants can replace running out heat sources or they can be installed to satisfy growing heat demand. To achieve information about the structure of the existing heat sources in the district heating industry a survey among members of the district heating association was carried out which represents roughly ¾ of the heat supply. Figure 6 displays the age structure of the district heating sources looking at their number and power. The annual power installation after 1975 is roughly 800 MW and the average power per heat source ranges between 20 and 40 MW. The survey also brought forth that the enterprises expect an average district heating growth rate of 1.3 % per annum in the near future which results in a growth of the annual power demand around 450 MW.

The analysis of the technical potential for nuclear heating plants results in the amount of plants of different power levels shown in table 1. This analysis considers the existing structures of district heating enterprises of networks and of the heat sources. The ranges result from different ways of implementation. The technical potential in the field of the district heating system has a total power of 9.8 to 14.3 GW which matches 30 to 45 % of todays installed capacity. This potential would be opened up by heating reactors of different power levels.

The low temperature heat market and its local demand distribution according to the distribution of the population offer a theoretical potential for heating reactors which is an order of magnitude larger than the technical potential in the district heating system. The investigated theoretical potential includes about one third of the low temperature heating market so that there is a large enough potential for heating reactors in the Federal Republic of Germany to justify their further development.

Environmental benefits from applying nuclear heating plants

Using nuclear energy can relieve the environmental stress by reducing the consumption of fossil fuels and the following emissions of air pollutants including carbon dioxide. Looking at the pollutants sulfur dioxide and nitrogen oxides district heating plants can additionally achieve high reduction levels but – besides of interfuel substitution – there is no economical technical method to lessen CO_2-emissions except for the use of non-fossil fuels where nuclear energy can help a good deal. After all it must be pointed out that the CO_2-emissions of the existing district heat production have only the small portion of about 3 % of the country wide emissions.

Summary – what must be done to have nuclear heating plants contribute to the energy production?

The application of nuclear energy must generally be accepted which first of all results in a continuing nuclear electricity production. The nuclear energy will then get benefit from this general acceptance for its use in the heating market.

The reduction of environmental stress especially by the emission of greenhouse gases like CO_2 might gain importance looking at the use of nuclear energy in future.

If nuclear heating plants shall contribute successfully to the future heat production in line with market requirements their cost and other aspects like licensing practice must allow obvious economic advantages compared to other typical heat sources.

To build up technical and economic experience on heating reactors and to demonstrate their safety under practical conditions the construction of prototype plants would be necessary.

According to the available knowledge at the moment nuclear heating plants seem to be an interesting option for the heat supply of the future. A thorough examination of possibilities for the future use seems to be useful. The commercial use of this heat source is however not expected until the next century. But the basis of the assessment of nuclear heat production might be changed by the today indicated demand for reduction of fossil fuel burning and by the discussion about the social cost of the energy production.

■